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Annoyance Caused by Aircraft En Route Noise

David A. McCurdy

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Abstract

A laboratory experiment was conducted to quantify the annoyance response of people on the ground to en route noise generated by aircraft at cruise conditions. The en route noises were ground-level recordings of eight advanced turboprop aircraft flyovers and six conventional turbofan flyovers. The eight advanced turboprop en route noises represented the NASA Propfan Test Assessment aircraft operating at different combinations of altitude, aircraft Mach number, and propeller tip speed. The conventional turbofan en route noises represented six different commercial airliners. The overall durations of the en route noises varied from approximately 40 to 160 sec. In the experiment, 32 subjects judged the annoyance of the en route noises as well as recordings of both the takeoff and landing noises of each of 5 conventional turboprop and 5 conventional turbofan aircraft. Each of the noises was presented at three sound pressure levels to the subjects in an anechoic listening room. Analyses of the judgments found small differences in annoyance between three combinations of aircraft type and operation. Current tone and duration corrections did not significantly improve en route noise annoyance prediction. The optimum duration-correction magnitude for en route noise was approximately 1 dB per doubling of effective duration.

Introduction

Concerns about the impact of aircraft noise on people have traditionally centered around the takeoff and landing operations of aircraft in the vicinity of airport terminals. The development of advanced turboprop (propfan) propulsion systems, modifications to air corridors, and the desire to maintain a natural environment in national parks and recreation areas have now focused attention on the impact at ground level of the en route noise produced by aircraft at cruise conditions and altitudes (ref. 1). Compared with terminal-area noise (i.e., takeoff and landing noise), en route noise is characterized by relatively low noise levels, a lack of high-frequency spectral content, and long durations. Much research has been directed towards understanding and quantifying the annoyance caused by terminal-area aircraft noise, but relatively little research has been conducted for en route noise.

To address this need, a laboratory experiment was conducted to quantify the annoyance response of people on the ground to en route noise generated by aircraft at cruise conditions. The specific objectives were: (1) to compare the annoyance responses to en route noise with the annoyance responses to takeoff and landing noise; (2) to compare the annoyance responses to en route noise of advanced turboprop aircraft with the annoyance responses to en route noise of conventional turbofan aircraft; (3) to determine the ability of current aircraft noise measurement procedures and corrections to predict annoyance to en route noise; and (4) to determine whether modifications to the duration-correction method would improve the prediction of annoyance to en route noise.

Noise Metrics, Symbols, and Abbreviations

Noise Metrics

EPNL	effective perceived noise level, dB
L_A	A-weighted sound pressure level, dB
L_D	D-weighted sound pressure level, dB
LL_Z	Zwicker loudness level, dB
PL	perceived level (Stevens Mark VII procedure), dB
PNL	perceived noise level, dB

Detailed descriptions of the noise metrics used in this report can be found in references 2 and 3.

Symbols and Abbreviations

ATP	advanced turboprop
a_0, a_1, a_2	constant coefficients
D^*	duration correction based on a non-optimum duration-correction magnitude expressed in terms of decibels per doubling of effective duration, dB

D'	duration correction based on the optimum duration-correction magnitude expressed in terms of decibels per doubling of effective duration, dB
D_{10}	duration-correction method in which the effective duration is determined from an integration of the energy between the 10-dB down points of a noise as done in the EPNL duration-correction method (ref. 2)
D_{15}	duration-correction method in which the effective duration is determined from an integration of the energy between the 15-dB down points of a noise instead of the 10-dB down points
D_{20}	duration-correction method in which the effective duration is determined from an integration of the energy between the 20-dB down points of a noise instead of the 10-dB down points
FAR	Federal Aviation Regulation
h	aircraft cruise altitude, ft
$L_{\max}$	maximum noise measurement level (without duration correction), dB
L_S	subjective noise level, dB
M	Mach number
PTA	Propfan Test Assessment
p	probability
T_1	EPNL tone-correction method (ref. 2)
T_2	tone-correction method identical to T_1 except that no corrections are applied for tones below the 500-Hz 1/3-octave band
v	aircraft speed, knots
v_t	propeller tip speed, ft/sec

Experimental Method

Test Facility

The anechoic listening room in the Langley Acoustics Research Laboratory (fig. 1) was used as the test facility in the experiment. This room, which has a volume of 20 m^3 and an A-weighted ambient noise level of 15 dB, provides an essentially echo-free environment. This environment minimizes the possibility of standing waves affecting the data. The monophonic recordings of the aircraft noise stimuli were played on a studio-quality tape recorder using a noise reduction system to reduce tape hiss. The commercially available noise reduction system, which provided a nominal 30-dB increase in signal-to-noise ratio, reduced tape hiss to inaudible levels. The stimuli were presented to the subjects using a special speaker system consisting of one high-frequency unit and one low-frequency unit. The high-frequency unit had a frequency range of 100 Hz to 10 000 Hz, and the low-frequency unit had a frequency range of 30 Hz to 100 Hz.

Test Subjects

Thirty-two subjects were randomly selected from a pool of local residents with a wide range of socioeconomic backgrounds and were paid to participate in the experiment. All test subjects were given audiograms prior to the experiment to verify normal hearing. Table I gives the sex and age data for the subjects in each experiment.

Noise Stimuli

The noise stimuli used in the experiment consisted of loudspeaker-reproduced recordings of actual flight operations. Thirty-four noises were presented to the test subjects at three nominal L_D levels of 60, 70, and 80 dB. Six additional presentations of a reference noise were included for a total of 108 noise stimuli. The 34 noises consisted of 8 advanced turboprop en route noises, 6 conventional turbofan en route noises, 10 conventional turboprop takeoff and landing noises, and 10 conventional turbofan takeoff and landing noises.

Advanced turboprop en route noises. The eight advanced turboprop en route noises were recordings of the NASA Propfan Test Assessment (PTA) aircraft shown in figure 2. The PTA aircraft is a modified Gulfstream Aerospace GII with an advanced turboprop engine installed on the port wing. The advanced turboprop consisted of a single-rotating, 8-blade, 9-ft-diameter propfan driven by a modified industrial gas turbine engine through a modified reduction gearbox (ref. 4). The recordings were obtained by using ground-level microphones during level flyover at cruise conditions with the aircraft's original engines operating at flight idle. The eight noises used in the experiment represent the different combinations of altitude, aircraft Mach number, and propeller tip speed shown in table II. The overall durations of the 8 noises used in the experiment varied from approximately 40 to 160 sec. The variations in duration resulted from the variations in altitude and Mach number and from the truncation of the beginning and ending of some noises necessitated by extraneous transient background noises.

The L_A time histories and the 1/3-octave-band spectra at peak L_A of the highest level presentations of the advanced turboprop en route noises are given in figure 3.

Conventional turbofan en route noises. The six conventional turbofan en route noises were recordings of commercial airliners made with ground-level microphones. Table III provides the type of aircraft, altitude, and speed for each noise. The overall durations of the six noises varied from approximately 40 to 160 sec. As with the advanced turboprop en route noises, the beginning and ending of some noises were truncated because of extraneous transient background noise. The L_A time histories and the 1/3-octave-band spectra at peak L_A of the highest level presentation of the conventional turbofan en route noises are given in figure 4.

Takeoff and landing noises. Recordings of both the takeoff and landing of each of five conventional turboprop and five conventional turbofan aircraft were included in the experiment for comparison with the en route noise stimuli. The types of aircraft used and some specifications of each are given in table IV. The recordings of the conventional turbofan aircraft were made on the centerline of the extended runway approximately 5000 m from the brake release point. The conventional turboprop aircraft recordings were made at several different airports, and the distances from the brake release point varied. At each location, the turboprop aircraft recordings were made on or near the centerline of the extended runway. Because of the higher flight profiles and lower source noise levels of the turboprop aircraft, the recording sites for the turboprop aircraft were located closer to the brake release point than those for the turbofan aircraft. Microphones were located approximately 1.2 m above ground level over dirt or grass. The overall durations of the 20 noises varied from approximately 10 to 50 sec. The L_A time histories and the 1/3-octave-band spectra at peak L_A of the highest level presentations of the takeoff and landing of each conventional turboprop and conventional turbofan are given in figures 5 and 6, respectively.

Reference noise. In addition to the three presentations made as part of the conventional turbofan takeoff stimuli, the Boeing 727 takeoff recording was presented at six other L_D levels of 50, 55, 65, 75, 85, and 90 dB. As a result of these additional presentations, a total of nine Boeing 727 takeoff stimuli, ranging in L_D levels from 50 to 90 dB in 5-dB increments, were presented to the test subjects. These nine stimuli were used as reference stimuli in the analyses to convert subjective responses to subjective decibel levels.

Experiment Design

Numerical category scaling was chosen as the psychophysical method for the experiment. The choice was made to maximize the number of stimuli that could be judged in the fixed amount of time available. The scale selected was a unipolar, 11-point scale from 0 to 10. The end points of the scale were labeled "EXTREMELY ANNOYING" and "NOT ANNOYING AT ALL." The term "ANNOYING" was defined in the subject instructions as "UNWANTED, OBJECTIONABLE, DISTURBING, OR UNPLEASANT."

The stimuli were divided into two sets of four tapes. The first set of tapes contained all the stimuli in the experiment. The second set contained the same stimuli as the first but in reverse order. There were 27 stimuli per tape. The stimuli were divided between tapes so that each aircraft type, aircraft operation, and sound level were about equally represented on each tape. The order of the stimuli on the tape was then randomly selected. The orders for each tape are given in table V, as indicated by the arrows. A period of approximately 10 sec was provided after each stimulus for the subjects to make and record their judgments. Each tape served as one of four test sessions for the subjects and required approximately 40 min for playback.

The 32 test subjects in the experiment were divided into 16 groups of 2 subjects. The first four tapes were presented to eight groups of subjects, and the second four tapes were presented to the other eight groups of subjects. To prevent subject fatigue and other temporal effects from unduly influencing the results, the order in which the tapes were presented was varied to provide a balanced presentation. Table VI gives the order of presentation used for the tapes in the experiment.

Procedure

Upon arrival at the laboratory, the subjects were seated in the test facility and each was given a set of instructions and a consent form. Copies of these items are given in the appendix. After reading the instructions and completing the consent forms, the subjects were given a brief verbal explanation of the cards used for recording judgments and were asked if they had any questions. Four practice stimuli were then presented to the subjects while the test conductor remained in the test facility. In order for the subjects to gain experience in scoring the sounds, they were instructed to make and record judgments of the practice stimuli. After asking again for any questions about the test, the test conductor issued scoring cards for the first session and left the facility. Then, the first of four test sessions began. After the conclusion of each session, the test conductor reentered the test facility, collected the scoring cards, and issued new scoring cards for the next session. Between the second and third sessions, the subjects were given a 15-min rest period outside the test facility.

Results and Discussion

Acoustic Data Analyses

Each noise stimulus was analyzed to provide 1/3-octave-band sound pressure levels from 20 Hz to 20 kHz for use in computing a selected group of noise metrics. The measurements were made with a 1.27-cm-diameter condenser microphone and a real-time, 1/3-octave analysis system that used digital filtering. The microphone was located at ear level midway between the two seats. No subjects were present during the measurements. A total of five noise metrics were computed in the analyses. They included the simple weighting procedures L_A and L_D and the more complex calculation procedures $\mathrm{LL_Z}$, PL, and PNL.

Twelve variations of each of the five noise metrics were calculated. The first was the peak or maximum level that occurred during the flyover noise. Two other variations were calculated by applying two different tone corrections. Nine more variations were attained by applying duration corrections based on three different integration periods to the non-tone-corrected level and the two tone-corrected levels. The first duration-correction integration period D_{10} and the first tone correction T_1 are identical to those used in the effective perceived noise level procedure defined in the Federal Aviation Administration FAR 36 regulation (ref. 2). The second tone correction T_2 is identical to the first except that no corrections are applied for tones identified in bands with center frequencies less than 500 Hz. The second and third duration-correction integration periods D_{15} and D_{20} are identical to the first except that the duration correction is based on an integration of the energy between the 15- and 20-dB down points of the noise instead of the 10-dB down points.

Subjective Data Analyses

The means (across subjects) of the judgments were calculated for each stimulus in the experiment. To obtain a subjective scale with meaningful units of measure, these mean annoyance scores were converted to subjective noise levels L_S with decibel-like properties by the following process. Included in the experiment for the purpose of converting the mean annoyance scores to L_S values were nine presentations of a Boeing 727 takeoff recording. The L_D levels of the nine presentations were 50, 55, 60, 65, 70, 75, 80, 85, and 90 dB. Third-order polynomial regression analyses were performed on data obtained for these nine reference stimuli. The dependent variable was the calculated PNL, and the independent variable was the mean annoyance score for each of the nine reference stimuli. Figure 7 presents the data and the resulting best-fit curve. The regression equation was then used to predict the level of the Boeing 727 takeoff noise that would produce the same mean annoyance score as each of the other noise stimuli in the experiment. These levels were then considered as the subjective noise level for each stimulus.

Comparison of Aircraft Types and Operations

Figure 8 compares the annoyance responses to PTA aircraft at cruise, conventional turbofan aircraft at cruise, and conventional turboprop and turbofan aircraft takeoffs and landings. The figure plots subjective noise level versus L_A for each of the three combinations of aircraft type and operation. Simple linear regression lines for each of the three combinations are also shown. For a given value of L_A, the conventional turbofan cruise noises were slightly more annoying than the PTA cruise noises. Although the differences in annoyance are small, indicator (dummy) variable analyses for L_A show significant differences in slope and intercept between the appropriate regressions for the three sets of noises. Figure 9 uses duration-corrected L_A to compare the annoyance responses to PTA aircraft at cruise, conventional turbofan aircraft at cruise, and conventional turboprop and turbofan aircraft takeoffs and landings. When duration corrections are added to L_A, the conventional turbofan cruise noises are slightly less annoying than the PTA cruise noises. This is the reverse of the results shown in figure 8 for L_A without duration corrections. As in the previous figure, indicator variable analyses indicate significant differences in slope and intercept between the appropriate regressions for the three types of noises. Figure 10 uses EPNL to compare the annoyance responses to PTA aircraft at cruise, conventional turbofan aircraft at cruise, and conventional turboprop and turbofan aircraft takeoffs and landings. Results are similar to those for duration-corrected L_A in figure 9.

Figures 8 to 10 compare the three combinations of aircraft type and operation in terms of three commonly used noise measurements—L_A, duration-corrected L_A, and EPNL. Comparisons using the other combinations of noise measurement procedures and corrections yielded similar results. Small, but significant, differences in annoyance response were found between the PTA advanced turboprop en route noises, the conventional turbofan en route noises, and the conventional turboprop and turbofan takeoff and landing noises. However, the difference in annoyance response between the PTA advanced turboprop en route noises and the conventional turbofan en route noises varied depending on the combination of measurement procedure and corrections considered.

Comparison of Noise Metrics for En Route Noise

When determining how to most accurately predict the annoyance caused by aircraft noise, the questions that must be answered are which noise measurement procedure should be used and which corrections, if any, should be applied to the measurement procedure. The answers to these questions can vary depending upon what types of aircraft and operations are under consideration. To investigate the prediction ability of the noise measurement procedures and corrections, the correlation coefficient between the subjective noise level L_S and the calculated noise level was determined for each combination of measurement procedure and corrections. The correlation coefficients were compared by using a two-tailed t-test for the significance of difference ($p \leq 0.05$) between correlation coefficients when samples are not independent (ref. 5). The higher the correlation coefficient, the better the prediction accuracy. The correlation coefficients for the en route noise stimuli are given in table VII. The following results are based on the statistical comparisons of the correlation coefficients.

Comparisons of the results in table VII indicate that, in all but a few cases, basing the duration correction on the 15- or 20-dB down points instead of the 10-dB down points did not significantly improve annoyance prediction. In most cases, the addition of duration corrections based on the 10-dB down points did not improve annoyance prediction. In all but one of the cases where the addition of the duration correction improved the correlation coefficient, the improvement was not significant. The one exception was L_A with T_1 tone corrections. In this case, the improvement in annoyance prediction that resulted from the addition of the duration correction was statistically significant.

The effect of the addition of tone corrections on annoyance prediction differed, depending on whether a duration correction was added. For the cases with duration corrections, annoyance prediction improved when either of the tone corrections, T_1 or T_2, was added. The improvements in correlation coefficient that result from the T_1 tone correction were significant, except for the case of L_A with duration corrections. The improvements provided by the T_2 tone correction were significant in all cases. Except for duration-corrected L_A, the T_1 tone corrections resulted in higher correlation coefficients than the T_2 tone corrections. However, the difference was not significant, except in the case of duration-corrected LL_Z. For the cases with no duration corrections, the T_1 tone correction improved the correlation coefficient only for LL_Z, and the improvement was not significant. The addition of the T_2 tone correction resulted in improved correlation coefficients in four of five cases, but these improvements were not significant either.

These results indicate that the addition of tone corrections and/or duration corrections does not significantly improve, in a consistent manner, the prediction of annoyance to en route noise. Comparison of the peak levels (i.e., the levels without corrections) of the different measurement procedures indicates that PNL has the highest correlation coefficient and L_A has the lowest correlation coefficient. The only significant differences between the five peak levels were that the correlation coefficients for PNL and L_D were both significantly greater than the correlation coefficient for L_A.

The L_A with D_{10} duration corrections and T_2 tone corrections had the highest correlation coefficient of the metrics considered and was therefore, strictly speaking, the best predictor of annoyance to en route noise. However, as indicated in the preceding paragraphs, statistical comparisons of the correlation coefficients indicate that duration and tone corrections do not significantly improve annoyance prediction. Comparison of the correlation coefficients for peak L_A and duration-corrected L_A with T_2 tone corrections indicates no significant difference. Of the peak levels considered, PNL had the highest correlation coefficient. Direct comparison of the correlation coefficient for peak PNL and duration-corrected L_A with the T_2 tone correction also indicates no significant difference. These analyses indicate that, of the noise metrics considered, PNL without tone and duration corrections is the most appropriate metric for predicting annoyance to en route noise.

Optimum Duration-Correction Magnitudes

The duration corrections discussed in the preceding section were based on the duration-correction magnitude used in the Federal Aviation Administration's EPNL calculation procedure for aircraft certification (ref. 2). This method assumes that a doubling of effective duration has the same effect on annoyance as a 3-dB increase in level. (Effective duration is determined from an integration of the energy between the 10-dB down points of a noise (refs. 2 and 3).) This 3-dB duration-correction magnitude has been shown to be the optimum (i.e., correct) value for the noise durations of aircraft takeoff and landing operations (ref. 6). However, 3 dB may not be the optimum duration-correction magnitude for the very long durations associated with en route noise. In other words, for very long durations, a doubling of effective duration may have an effect on annoyance equivalent to an increase in level of some value other than 3 dB. To determine the optimum duration-correction magnitude for en route noise, the analysis described in this section was performed on the data from this experiment.

If the magnitude on which a duration correction is based is the optimum magnitude, then a unit change in the duration correction represents the same change in annoyance as a unit change in the maximum level of a noise. Therefore, the subjective noise levels can be represented by the linear equation

$$L_S = a_0 + a_1\left(L_{\max} + D'\right) \tag{1}$$

where L_S is the subjective noise level, $L_{\max}$ is the maximum level, and D' is the duration correction based on the optimum magnitude. This equation can be expanded to the form

$$L_S = a_0 + a_1 L_{\max} + a_1 D' \tag{2}$$

However, if the magnitude on which a duration correction is based is not the optimum magnitude, then a unit change in the duration correction does not represent the same change in annoyance as a unit change in the maximum level of a noise. Therefore, for duration corrections calculated by using a nonoptimum magnitude (and if the maximum levels and durations are not correlated), the equation best fitting the data would be of the form

$$L_S = a_0 + a_1 L_{\max} + a_2 D^* \tag{3}$$

where a_1 is not equal to a_2 and D^* is the duration correction based on the nonoptimum magnitude. Combining equations (2) and (3) yields

$$a_1 D' = a_2 D^* \tag{4}$$

which gives

$$D' = \frac{a_2}{a_1} D^* \tag{5}$$

Duration corrections based on 3 dB per doubling of effective duration (i.e., the difference between the duration-corrected level and the respective maximum level for each noise metric) were used in multiple regression analyses of the form of equation (3). The optimum duration-correction magnitudes D' were then calculated from equation (5) with D^* set equal to 3 dB per doubling of effective duration. These calculations were made for each of the noise metrics for the PTA en route noise stimuli, the conventional turbofan en route noise stimuli, the combined set of en route noise stimuli, and the conventional turboprop and turbofan takeoff and landing noise stimuli. The resulting optimum magnitudes, in terms of equivalent decibels per doubling of effective duration, are given in table VIII for duration corrections based on the 10-dB down points. Tables IX and X give the optimum magnitudes for duration corrections based on the 15- and 20-dB down points.

The optimum magnitudes for the takeoff and landing noises agree very well with the 3-dB magnitude used in the EPNL duration correction. However, the optimum duration-correction magnitudes for the en route noises are considerably less than 3 dB. Based on these results, a duration-correction magnitude on the order of 1 dB per doubling of effective duration appears to be a more appropriate value for en route noise. Further analyses will determine whether this modification significantly improves annoyance prediction.

Comparison of Noise Metrics With Different Duration-Correction Magnitudes

To investigate whether a duration correction based on 1 dB per doubling of effective duration would improve the prediction ability of the noise measurement procedures and corrections, the correlation coefficient between the subjective noise level L_S and the calculated noise level was determined for each combination of measurement procedure, tone correction, and modified duration correction. As done previously, the correlation coefficients were compared by using a two-tailed t-test for the significance of difference ($p \leq 0.05$) between correlation coefficients when samples are not independent (ref. 5). The higher the correlation coefficient, the better the prediction accuracy. The correlation coefficients of the modified noise metrics for the en route noise stimuli are given in table XI. The coefficients in table XI that are significantly greater than the corresponding coefficients in table VII for the standard duration-correction magnitude of 3 dB are marked with an asterisk. Comparison of tables VII and XI shows that the duration-correction magnitude of 1 dB yielded a higher correlation coefficient than the 3-dB magnitude for every noise metric variation except the tone-corrected L_A cases. However, only about half the increases represented significant increases in annoyance prediction.

Since this result for a magnitude of 1 dB is not completely conclusive, the analysis was repeated by using the optimum duration-correction magnitudes for each noise metric variation for the combined set of en route noises as given in tables VIII to X. The resulting correlation coefficients are given in table XII. None of the coefficients in table XII are significantly greater than the corresponding coefficients in table XI for the modified duration-correction magnitude of 1 dB. The coefficients marked with an asterisk in table XII are significantly greater than the corresponding coefficients in table VII for the standard duration-correction magnitude of 3 dB. Comparisons of tables VII and XII show that the optimum duration-correction magnitudes yielded a higher correlation coefficient than the 3-dB magnitude for every noise metric variation, including the tone-corrected L_A cases. However, as with the 1-dB magnitude coefficients, only about half the increases represented significant increases in annoyance prediction.

Comparisons within tables XI and XII indicate that basing the duration corrections on the 15- or 20-dB down points instead of the 10-dB down points did not improve annoyance prediction. This result is similar to the 3-dB magnitude case. However, unlike the 3-dB magnitude results, the addition of duration corrections based on the 1-dB and optimum magnitudes did improve annoyance prediction in almost every instance. The increase, however, was not significant in most cases. The increase was significant for L_A, L_A with T_1 tone corrections, and L_A with T_2 tone corrections for both the 1-dB and the optimum magnitude cases. The PNL with T_1 tone corrections and P_L with T_1 tone corrections also had significant increases in the 1-dB magnitude case.

The effect on annoyance prediction of the addition of tone corrections to the metrics with reduced duration-correction magnitudes was to improve prediction in almost every case. The T_2 tone correction did better than the T_1 tone correction in all but one case. However, the improvement provided by T_1 and T_2 tone corrections was significant in only about half the cases.

Comparisons of the peak levels (i.e., the levels without corrections) and the duration-corrected levels with T_2 tone corrections for each measurement procedure in tables XI and XII yielded similar inconclusive results. The addition of corrections improved annoyance prediction, but the difference was significant in only about half the cases. Comparing the noise metric variation that had the highest correlation (D_{15} and D_{20} values not considered) from each of tables XI and XII—duration-corrected PL with T_2 tone corrections and duration-corrected L_A with T_2 tone corrections—with peak PNL showed no significant difference in the correlation coefficients at the 0.05 probability level. However, the coefficient for PNL with T_2 tone corrections and duration corrections based on a 1-dB magnitude was significantly greater than the coefficient for peak PNL.

These results indicate that when duration corrections are based on magnitudes of approximately 1 dB per doubling of effective duration, the addition of tone corrections and duration corrections improves the prediction of annoyance to en route noise, at least in terms of increasing the correlation coefficient. However, since the resulting improvements are not consistently statistically significant, it is difficult to conclude with certainty that the corrections should be used. Most of the improvements that were not statistically significant at the 0.05 level would have been significant at the 0.10 level. A definitive answer would best be obtained by conducting another test, in which the durations and tonal content of the stimuli were more systematically chosen and controlled.

Influence of Other Variables

In addition to the noise metrics, several quantitative physical parameters were considered as possible predictors of annoyance response to en route noise. They were overall duration, aircraft cruise altitude, aircraft cruise Mach number, and propeller tip speed at cruise for the PTA en route noise stimuli; and overall duration, aircraft cruise altitude, and aircraft cruise speed for the conventional turbofan en route noise stimuli. Overall duration was studied separately from the other parameters for the combined set of en route noise stimuli. Overall duration is the time from the start of the noise stimulus to the end of the noise stimulus (i.e., the total time that the stimulus is audible). The other parameters were studied within the PTA and conventional turbofan subsets of stimuli, because the parameters, or the way they were measured, differed between the subsets. The effects of the parameters in conjunction with various combinations of PNL, with and without duration (based on 3 dB per doubling of effective duration and 10-dB down points) and tone (T_1 and T_2) corrections, were studied by using multiple regression analyses with L_S as the dependent variable. Regression models, including the noise metric and each combination of one or more of the parameters, were determined and compared by using the models comparison approach detailed in reference 7. The addition of the parameters did not improve the regression models. Therefore, no effect on annoyance of any of the parameters is indicated.

Conclusions

A laboratory experiment was conducted to quantify the annoyance response of people on the ground to en route noise generated by aircraft at cruise conditions. Thirty-two test subjects judged the annoyance of 24 Propfan Test Assessment (PTA) advanced turboprop en route noise stimuli, 18 conventional turbofan en route noise stimuli, and 60 conventional turboprop and turbofan takeoff and landing noise stimuli. Analyses of the resulting data compared annoyance responses to different aircraft types and operations, examined the ability of current noise measurement and correction procedures to predict annoyance to en route noise, and calculated optimum duration-correction magnitudes for en route noise.

Based on the results presented in this paper, the following conclusions were noted:

1. Small, but significant, differences in annoyance response were found between the PTA advanced turboprop en route noises, the conventional turbofan en route noises, and the conventional turboprop and turbofan takeoff and landing noises. However, the difference in annoyance response between the PTA advanced turboprop en route noises and the conventional turbofan en route noises varied depending upon the noise metric considered.

2. Basing the duration correction on the noise between the 15- or 20-dB down points instead of the noise between the 10-dB down points did not improve the prediction of annoyance to en route noise.

3. The prediction of annoyance to en route noise was not significantly improved by the addition of a duration correction based on the magnitude of 3 dB per doubling of effective duration used in effective perceived noise level (EPNL).

4. In most cases, tone corrections did not significantly improve prediction of annoyance to en route noise.

5. Of the noise metrics considered, PNL without tone and duration corrections was the most appropriate noise metric for predicting annoyance to en route noise.

6. The optimum duration-correction magnitude for en route noise is approximately 1 dB per doubling of effective duration instead of the 3 dB per doubling of effective duration used for takeoff and landing noise.

7. The addition of duration corrections based on the reduced correction magnitude in conjunction with tone corrections tended to improve prediction of annoyance to en route noise. Whether or not the improvement was statistically significant depended on which noise measurement procedure was used and the exact magnitude of the reduced duration correction.

8. No effects of overall duration, aircraft cruise altitude, aircraft cruise Mach number, aircraft cruise speed, or cruise propeller tip speed on annoyance to en route noise were found.

NASA Langley Research Center
Hampton, VA 23665-5225
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Table I. Data on Test Subjects

Sex	Number of participants	Mean age	Median age	Age range
Male	12	30	25.5	18 to 49
Female	20	40	42	18 to 58
All subjects	32	37	39.5	18 to 58

Table II. Nominal Flight Conditions for PTA Aircraft En Route Noises

PTA noise number	Altitude, ft	Aircraft Mach number	Propeller tip speed, ft/sec
1	30 000	0.70	800
2	15 000	.70	↓
3	15 000	.50	↓
4	9 000	.50	↓
5	2 000	.50	↓
6	30 000	.70	620
7	30 000	.70	700
8	30 000	.77	840

Table III. Flight Conditions for Conventional Turbofan Aircraft En Route Noises

Airplane	Altitude, ft	Speed, knots
Boeing 727	31 000	455
Boeing 737	35 000	434
Boeing 757	37 000	509
Boeing 767	28 000	460
McDonnell Douglas DC-9	30 000	477
McDonnell Douglas DC-10	37 000	521

Table IV. Conventional Turboprop and Turbofan Aircraft for Which Takeoff and Landing Noises Were Included in Experiment

Aircraft	Number of engines	Engine type	Maximum takeoff weight, kg
de Havilland Canada DHC-7 Dash 7	4	Turboprop	20000
Lockheed P-3	4	↓	61200
NAMC YS-11	2	↓	24500
Nord 262	2	↓	10600
Shorts 330	2	↓	10300
Airbus Industrie A-300	2	Turbofan	≥142000
Boeing 707	4	↓	≥117000
Boeing 727-200	3	↓	86900
McDonnell Douglas DC-9	2	↓	≥41100
McDonnell Douglas DC-10	3	↓	≥206400

Table V. Presentation Order of Stimuli on Tapes

Practice tape	Tape 1 ↓	Tape 2 ↓	Tape 3 ↓	Tape 4 ↓
PTA2 C 70	PTA2 C 70	N262 L 60	DC-9 T 80	DC10 L 60
B707 T 80	S330 T 80	B727 T 70	B727 C 60	PTA3 C 70
B737 C 60	PTA5 C 60	LP-3 T 80	YS11 L 70	B757 C 80
LP-3 L 70	DC-9 T 70	DC10 C 80	PTA1 C 60	S330 L 60
	YS11 L 60	PTA7 C 70	B707 T 70	B707 T 60
	B727 T 90	B757 C 60	PTA2 C 80	PTA6 C 80
	DD-7 T 60	PTA8 C 80	B727 L 60	DD-7 T 70
	PTA3 C 60	N262 T 70	DD-7 T 80	DC-9 C 60
	B757 C 70	B707 L 80	S330 T 60	PTA2 C 60
	DC10 T 80	LP-3 L 70	DC10 C 70	A300 T 70
	LP-3 L 60	YS11 T 60	PTA5 C 70	N262 T 80
	B727 T 60	B737 C 60	S330 L 80	YS11 L 80
	DD-7 L 70	DD-7 L 80	B727 T 50	PTA8 C 60
	YS11 T 70	S330 L 70	LP-3 T 70	B727 T 55
	DC-9 C 80	DC-9 T 60	DD-7 L 60	S330 T 70
	DC10 C 60	PTA6 C 60	PTA4 C 80	PTA4 C 70
	B707 L 70	B727 T 85	N262 T 60	A300 L 80
	A300 T 80	PTA3 C 80	B767 C 80	LP-3 T 60
	PTA7 C 80	DC-9 C 70	PTA8 C 70	YS11 T 80
	B727 C 70	A300 L 60	LP-3 L 80	B767 C 70
	DC-9 L 60	B727 L 70	PTA7 C 60	N262 L 70
	PTA6 C 70	B707 T 80	B727 T 75	B707 L 60
	PTA1 C 80	PTA1 C 70	DC10 L 80	PTA5 C 80
	B727 L 80	PTA4 C 60	A300 L 70	B727 T 80
	DC10 L 70	B727 T 65	B737 C 80	DC10 T 60
	B767 C 60	DC-9 L 80	A300 T 60	B737 C 70
	N262 L 80	B727 C 80	DC10 T 70	DC-9 L 70
	Tape 5 ↑	Tape 6 ↑	Tape 7 ↑	Tape 8 ↑

Stimuli key				
Aircraft type				
Advanced turboprop	Conventional turbofan	Conventional turboprop	Operation type	Nominal L_D
PTAn = Propfan	A300 = Airbus A-300	DD-7 = Dash 7	C = Cruise	50 = 50 dB
test assessment	B707 = Boeing 707	LP-3 = P-3	L = Landing	55 = 55 dB
aircraft noise	B727 = Boeing 727	N262 = Nord 262	T = Takeoff	60 = 60 dB
number n	B737 = Boeing 737	S330 = Shorts 330		65 = 65 dB
	B757 = Boeing 757	YS11 = YS-11		70 = 70 dB
	B767 = Boeing 767			75 = 75 dB
	DC-9 = DC-9			80 = 80 dB
	DC10 = DC-10			85 = 85 dB
				90 = 90 dB

Table VI. Order of Tapes Presented to Test Subjects

Test subject group	Tapes presented during session—			
	1	2	3	4
1	1	2	3	4
2	2	4	1	3
3	3	1	4	2
4	4	3	2	1
5	5	6	7	8
6	6	8	5	7
7	7	5	8	6
8	8	7	6	5
9	2	1	4	3
10	1	3	2	4
11	4	2	3	1
12	3	4	1	2
13	6	5	8	7
14	5	7	6	8
15	8	6	7	5
16	7	8	5	6

Table VII. Correlation Coefficients of Noise Metrics With Subjective Noise Level for Cruise Noise Stimuli

[Duration-correction magnitude is 3 dB per doubling of effective duration]

Noise measurement procedure	Tone-correction procedure	Correlation coefficient for—			
		No duration correction	D_{10}	D_{15}	D_{20}
L_A	No tone correction	0.9615	0.9692	0.9686	0.9692
	T_1	.9518	.9731	.9724	.9722
	T_2	.9603	.9740	.9739	.9739
L_D	No tone correction	0.9704	0.9544	0.9542	0.9551
	T_1	.9660	.9643	.9640	.9643
	T_2	.9722	.9623	.9622	.9630
PNL	No tone correction	0.9707	0.9597	0.9596	0.9601
	T_1	.9662	.9678	.9670	.9673
	T_2	.9712	.9663	.9664	.9668
PL	No tone correction	0.9704	0.9485	0.9517	0.9531
	T_1	.9673	.9638	.9635	.9645
	T_2	.9708	.9591	.9614	.9622
LL_Z	No tone correction	0.9697	0.9328	0.9377	0.9395
	T_1	.9719	.9510	.9524	.9538
	T_2	.9729	.9440	.9478	.9493

Table VIII. Optimum Duration-Correction Magnitudes Based on 10-dB Down Points

[Optimum duration-correction magnitudes are in decibels per doubling of effective duration]

Tone-correction procedure	Metric	PTA at cruise	Conventional turbofan at cruise	PTA and conventional turbofan at cruise	Conventional turboprop and turbofan at takeoff and landing
No tone correction	L_A	1.77	1.70	1.82	2.72
	L_D	1.26	1.29	.72	3.10
	PNL	1.02	1.12	.81	3.42
	PL	.54	1.66	.62	2.73
	LL_Z	.62	1.53	.07	2.81
Average		1.04	1.46	0.81	2.96
T_1	L_A	1.12	1.07	2.49	2.77
	L_D	1.08	.28	1.40	3.26
	PNL	.77	.91	1.59	3.56
	PL	.59	1.29	1.35	2.85
	LL_Z	.74	1.29	.67	2.93
Average		0.86	0.97	1.50	3.07
T_2	L_A	1.80	1.85	2.10	2.82
	L_D	1.27	1.47	.98	3.26
	PNL	1.34	1.34	1.19	3.59
	PL	1.10	1.89	1.06	2.82
	LL_Z	1.01	1.69	.46	2.89
Average		1.30	1.65	1.16	3.08
Grand average		1.07	1.36	1.16	3.04

Table IX. Optimum Duration-Correction Magnitudes Based on 15-dB Down Points

[Optimum duration-correction magnitudes are in decibels per doubling of effective duration]

Tone-correction procedure	Metric	PTA at cruise	Conventional turbofan at cruise	PTA and conventional turbofan at cruise	Conventional turboprop and turbofan at takeoff and landing
No tone correction	L_A	1.31	1.70	1.82	2.74
	L_D	.66	1.27	.67	3.12
	PNL	.57	1.18	.77	3.41
	PL	.60	1.75	.68	2.73
	LL_Z	.72	1.47	.11	2.80
Average		0.77	1.47	0.81	2.96
T_1	L_A	0.70	1.17	2.53	2.82
	L_D	.36	.40	1.38	3.25
	PNL	.10	.83	1.54	3.51
	PL	.17	1.36	1.33	2.87
	LL_Z	.27	1.32	.64	2.91
Average		0.32	1.02	1.48	3.07
T_2	L_A	1.52	1.86	2.14	2.83
	L_D	.72	1.48	.95	3.26
	PNL	1.02	1.38	1.18	3.56
	PL	1.15	1.92	1.12	2.81
	LL_Z	1.06	1.71	.50	2.87
Average		1.09	1.67	1.18	3.07
Grand average		0.73	1.39	1.16	3.03

Table X. Optimum Duration-Correction Magnitudes Based on 20-dB Down Points

[Optimum duration-correction magnitudes are in decibels per doubling of effective duration]

Tone-correction procedure	Metric	PTA at cruise	Conventional turbofan at cruise	PTA and conventional turbofan at cruise	Conventional turboprop and turbofan at takeoff and landing
No tone correction	L_A	1.32	1.76	1.86	2.75
	L_D	.71	1.34	.69	3.14
	PNL	.60	1.19	.79	3.35
	PL	.65	1.75	.71	2.73
	LL_Z	.75	1.47	.13	2.79
Average		0.81	1.50	0.84	2.95
T_1	L_A	0.66	1.15	2.52	2.83
	L_D	.33	.43	1.40	3.27
	PNL	.07	.97	1.57	3.55
	PL	.20	1.40	1.36	2.86
	LL_Z	.35	1.31	.67	2.92
Average		0.32	1.05	1.50	3.09
T_2	L_A	1.49	1.86	2.15	2.85
	L_D	.78	1.48	.98	3.27
	PNL	1.02	1.38	1.20	3.58
	PL	1.15	1.92	1.14	2.84
	LL_Z	1.09	1.72	.53	2.91
Average		1.11	1.67	1.20	3.09
Grand average		0.74	1.41	1.18	3.04

Table XI. Correlation Coefficients of Noise Metrics With a Modified Duration Correction and Subjective Noise Level for Cruise Noise Stimuli

[Duration-correction magnitude is 1 dB per doubling of effective duration]

Noise measurement procedure	Tone-correction procedure	Correlation coefficient for—			
		No duration correction	D_{10}	D_{15}	D_{20}
L_A	No tone correction	0.9615	0.9719	0.9713	0.9712
	T_1	.9518	.9660	.9652	.9651
	T_2	.9603	.9724	.9718	.9717
L_D	No tone correction	0.9704	*0.9720	*0.9716	*0.9717
	T_1	.9660	.9723	.9716	.9716
	T_2	.9722	*.9755	*.9751	*.9752
PNL	No tone correction	0.9707	*0.9725	*0.9721	*0.9722
	T_1	.9662	.9720	.9714	.9714
	T_2	.9712	.9752	.9749	.9749
PL	No tone correction	0.9704	*0.9714	*0.9718	*0.9719
	T_1	.9673	.9744	.9737	.9736
	T_2	.9708	*.9758	*.9760	*.9761
LL_Z	No tone correction	0.9697	*0.9657	*0.9664	*0.9667
	T_1	.9719	*.9734	*.9730	*.9731
	T_2	.9729	*.9724	*.9729	*.9731

*Correlation coefficient is significantly greater ($p \leq 0.025$) than corresponding correlation coefficient for noise metrics with duration corrections based on a magnitude of 3 dB per doubling of effective duration.

Table XII. Correlation Coefficients of Noise Metrics With Optimum Magnitude Duration Corrections and Subjective Noise Level for Cruise Noise Stimuli

[See tables VIII, IX, and X for optimum duration-correction magnitudes used for each noise metric]

Noise measurement procedure	Tone-correction procedure	Correlation coefficient for—			
		No duration correction	D_{10}	D_{15}	D_{20}
L_A	No tone correction	0.9615	0.9746	0.9738	0.9738
	T_1	.9518	.9740	.9731	.9729
	T_2	.9603	.9770	.9765	.9764
L_D	No tone correction	0.9704	*0.9723	*0.9719	*0.9720
	T_1	.9660	.9729	.9721	.9721
	T_2	.9722	*.9755	*.9751	*.9752
PNL	No tone correction	0.9707	*0.9726	*0.9723	*0.9723
	T_1	.9662	.9729	.9721	.9721
	T_2	.9712	.9753	.9750	.9750
PL	No tone correction	0.9704	*0.9720	*0.9722	*0.9722
	T_1	.9673	*.9749	.9741	.9741
	T_2	.9708	*.9759	*.9761	*.9762
LL_Z	No tone correction	0.9697	*0.9697	*0.9697	*0.9697
	T_1	.9719	*.9739	*.9735	*.9736
	T_2	.9729	*.9739	*.9740	*.9741

*Correlation coefficient is significantly greater ($p \leq 0.025$) than corresponding correlation coefficient for noise metrics with duration corrections based on a magnitude of 3 dB per doubling of effective duration.

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David A. McCurdy

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13. ABSTRACT *(Maximum 200 words)*
A laboratory experiment was conducted to quantify the annoyance response of people on the ground to en route noise generated by aircraft at cruise conditions. The en route noises were ground-level recordings of eight advanced turboprop aircraft flyovers and six conventional turbofan flyovers. The eight advanced turboprop en route noises represented the NASA Propfan Test Assessment aircraft operating at different combinations of altitude, aircraft Mach number, and propeller tip speed. The conventional turbofan en route noises represented six different commercial airliners. The overall durations of the en route noises varied from approximately 40 to 160 sec. In the experiment, 32 subjects judged the annoyance of the en route noises as well as recordings of both the takeoff and landing noises of each of 5 conventional turboprop and 5 conventional turbofan aircraft. Each of the noises was presented at three sound pressure levels to the subjects in an anechoic listening room. Analyses of the judgments found small differences in annoyance between three combinations of aircraft type and operation. Current tone and duration corrections did not significantly improve en route noise annoyance prediction. The optimum duration-correction magnitude for en route noise was approximately 1 dB per doubling of effective duration.

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